Higgs boson mass in NMSSM with right-handed neutrino

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Abstract

In order to have massive neutrinos, the right-handed neutrino/sneutrino superfield (N) need to be introduced in supersymmetry. In the framework of NMSSM (the MSSM with a singlet S) such an extension will dynamically lead to a TeV-scale Majorana mass for the right-handed neutrino through the SNN coupling when S develops a vev (the free Majorana mass term is forbidden by the assumed Z_3 symmetry). Also, through the couplings SNN and SH_uH_d, the SM-like Higgs boson (a mixture of H_u, H_d and S) can naturally couple with the right-handed neutrino/sneutrino. As a result, the TeV-scale right-handed neutrino/sneutrino may significantly contribute to the Higgs boson mass. Through an explicit calculation, we find that the Higgs boson mass can indeed be sizably altered by the right-handed neutrino/sneutrino. Such new contribution can help to push up the SM-like Higgs boson mass and thus make the NMSSM more natural.

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I. INTRODUCTION

Supersymmetry (SUSY) [1, 2] gives a natural solution to the hierarchy problem suffered by the Standard Model (SM). Also, it provides a good dark matter candidate and realizes the gauge coupling unification. Among the SUSY models, the Minimal Supersymmetric Standard Model (MSSM) [3] has been intensively studied. However, the recently discovered Higgs-like boson around 125 GeV caused a problem for this model, i.e., a 125 GeV Higgs boson requires a heavy stop or a large tri-linear coupling A_t and thus incurs the little hierarchy problem. Besides, the MSSM suffers from the μ-problem [4].

It is remarkable that both the little hierarchy problem and the μ-problem can be solved in the Next-to-Minimal Supersymmetric Standard Model (NMSSM) [5]. The NMSSM extends the MSSM by introducing a gauge singlet S. In this model the μ-problem is solved by the dynamical generation of the μ-term through the coupling SH_uH_d when S develops a vev, while the little hierarchy problem is solved by the generation of an extra tree-level mass term for the SM-like Higgs boson (thus the stop mass or A_t is no longer required to be unnaturally large).

Note that in order to have massive neutrinos, right-handed neutrino/sneutrino superfield(s) (N) need to be introduced in SUSY models. For the NMSSM with such right-handed neutrino/sneutrino field(s) [6], some intriguing features are present. Due to the assumed Z_3 symmetry, the free Majorana mass term for the right-handed neutrino is forbidden in the superpotential. Instead, a TeV-scale Majorana mass for the right-handed neutrino is dynamically generated through the SNN coupling when S develops a vev (note that such a TeV-scale majorana mass is too low for the see-saw mechanism and thus the neutrino Yukawa couplings H_uLN must be very small). In the same way, a TeV-scale mass for the right-handed sneutrino can also be generated, which can serve as a good dark matter candidate [8]. Further, through the couplings SNN and SH_uH_d, the SM-like Higgs boson (a mixture of H_u, H_d and S) can naturally couple with the right-handed neutrino/sneutrino. As a result, the TeV-scale right-handed neutrino/sneutrino may significantly contribute to the Higgs boson mass (in the MSSM with split SUSY, the right-handed neutrino/sneutrino can also make sizable contribution to the Higgs mass, as studied in [9]). In this paper we will perform an explicit calculation for such contribution.

This work is organized as follows. In Sec. II we present the spectrum and couplings

for the Higgs boson and right-handed neutrino/sneutrino. In Sec. III the renormalization scheme is described. Numerical results and discussions are given in Sec. IV. Finally, we give a summary in Sec.V.

II. HIGGS AND RIGHT-HANDED NEUTRINO/SNEUTRINO IN NMSSM

A. Model description

The NMSSM with a right-handed neutrino superfield N has a superpotential given by

$$W = W_{\rm NMSSM} + \lambda_N SNN + y_N H_u \cdot LN,$$
$$W_{\rm NMSSM} = Y_u H_u \cdot Q u_R - Y_d H_d \cdot Q d_R - Y_e H_d \cdot L e_R + \lambda S H_u \cdot H_d + \frac{1}{3}\kappa S^3, \tag{1}$$

where the flavor indices are omitted and the dot denotes the $SU(2)_L$ antisymmetric product. Since a global Z_3 symmetry is imposed, there are no supersymmetric mass terms (like $H_u H_d$, NN or SS) in the superpotential. Note that the terms NNN and SSN are gauge invariant but forbidden by R-parity. Although a bare Majorana mass term NN is forbidden in the superpotential, a TeV-scale Majorana mass can be generated through the coupling SNN when S develops a non-zero vev (v_s). Such a TeV-scale Majorana mass is too small for the conventional see-saw mechanism and thus the Yukawa coupling $y_N H_u LN$ should be very small ($y_N \ll 1$). The soft SUSY breaking terms for Higgs and right-handed sneutrino are given by (hereafter we use N and $\tilde{N}$ to denote respectively right-handed neutrino and sneutrino)

$$\begin{aligned} -\mathcal{L}_{\rm soft} \ =\ & M_{H_u}^2 |H_u|^2 + M_{H_d}^2 |H_d|^2 + M_s^2 |S|^2 + (\lambda A_\lambda H_u \cdot H_d S + \frac{\kappa}{3} A_\kappa S^3 + h.c.) \\ & + M_{\tilde{N}}^2 |\tilde{N}|^2 + (\lambda_N A_N S \tilde{N}\tilde{N} + h.c.) \end{aligned} \tag{2}$$

Here we neglected the mixing between left-handed and right-handed sneutrinos because the mixing is assumed to be suppressed by y_N. In the following we briefly discuss the neutral Higgs neutrino sectors.

B. The neutral Higgs sector

From Eq. (1) and Eq. (2) we get the Higgs potential

$$\begin{aligned} V &= \lambda^2(|H_u|^2|S|^2 + |H_d|^2|S|^2 + |H_u \cdot H_d|^2) + \kappa^2|S^2|^2 \\ &\quad +\lambda\kappa(H_u \cdot H_d S^* S^* + \text{h.c.}) + \frac{1}{4}\, g^2(|H_u|^2 - |H_d|^2)^2 \\ &\quad +\frac{1}{2}\, g_2^2|H_u^+(H_d^0)^* + H_u^0(H_d^-)^*|^2 + M_{H_u}^2|H_u|^2 + M_{H_d}^2|H_d|^2 + M_S^2|S|^2 \\ &\quad +(\lambda A_\lambda H_u \cdot H_d S + \frac{1}{3}\, \kappa A_\kappa\; S^3 + \text{h.c.}) \end{aligned} \tag{3}$$

where $g^2 = (g_1^2 + g_2^2)/2$ with g_1 and g_2 being the SM gauge coupling constants. Assuming H_u, H_d and S get vevs such that

$$H_u^0 = v_u + \frac{\text{Re}(H_R^0) + i\text{Im}(H_u^0)}{\sqrt{2}}, \quad H_d^0 = v_d + \frac{\text{Re}(H_d^0) + i\text{Im}(H_d^0)}{\sqrt{2}}, \quad S = v_s + \frac{S_R + iS_I}{\sqrt{2}} \tag{4}$$

we can get the mass terms for the Higgs fields, which are presented in [11]. Here we only show the conventions and give some brief comments:

1. The mass matrix for the CP-even neutral Higgs is obtained from the real components of the Higgs fields. In the basis $h^{bare} = [\text{Re}(H_u^0), \text{Re}(H_d^0), S_R]$ and using the minimization equations to eliminate the soft masses, one obtains three CP-even states (ordered in mass)

$$h_i = S_{ij} h_j^{bare} \tag{5}$$

with an orthogonal rotation S_{ij}.

2. The mass matrix for the CP-odd neutral Higgs is obtained form the imaginary components of the Higgs fields $[\text{Im}(H_u^0), \text{Im}(H_d^0), S_I]$. Its diagonalization is performed in two steps. First, one rotates it into a basis (A, S_I, G) where $G = -\sin\beta\text{Im}(H_u^0) + \cos\beta\text{Im}(H_d^0)$ is a massless Goldstone mode ($\tan\beta = v_u/v_d$ is the ratio of the vevs of the two Higgs doublets). Dropping the Goldstone mode, the remaining 2×2 mass matrix M_p^2 in the basis (A, S_I) can be diagonalized by an orthogonal 2×2 matrix P_{ij} into two physical CP-odd states a_i (ordered in mass):

$$\begin{aligned} a_1 &= P_{11}A + P_{12}S_I, \\ a_2 &= P_{21}A + P_{22}S_I. \end{aligned} \tag{6}$$

3. The neutralino mass matrix $\mathcal{M}_N$ in the basis $\psi^0 = (-i\lambda_1, -i\lambda_2, \psi_u^0, \psi_d^0, \psi_s)$ can be diagonalized by an rotation matrix N_{ij}. Then one obtains five eigenstates (ordered in mass) $\chi_i^0 = N_{ij}\psi_j^0$.

C. Right-handed neutrino/sneutrino sector

Since there is no Dirac mass term here, the mass spectrum of the right-handed neutrino sector is very simple. Denoting $\tilde{N} = R + iM$, there are only one CP-even right-handed sneutrino (denoted as R) and one CP-odd right-handed sneutrino (denoted as M). The right-handed neutrino is denoted as N. From Eq. (1) and Eq. (2) we can get the spectrum as

$$\begin{aligned} m_R^2 &= 4\lambda_N^2 v_s^2 + M_{\tilde{N}}^2 + 2\lambda_N v_s A_N + 2\lambda_N(\kappa v_s^2 - \lambda v_u v_d) \\ m_M^2 &= 4\lambda_N^2 v_s^2 + M_{\tilde{N}}^2 - 2\lambda_N v_s A_N - 2\lambda_N(\kappa v_s^2 - \lambda v_u v_d) \\ m_N &= 2\lambda_N v_s. \end{aligned} \tag{7}$$

With the above spectrum we can get the couplings between the Higgs and the right-handed neutrino/sneutrino. In the following we list the couplings which will be used in our later calculations:

$$V_{h_iRR} = \sqrt{2}\lambda_N\lambda\left(v_u S_{j2} + v_d S_{j1}\right) - \sqrt{2}\left(2\lambda_N\kappa v_s + 4\lambda_N^2 v_s + \lambda_N A_N\right) S_{j3}, \tag{8}$$

$$V_{h_iMM} = -\sqrt{2}\lambda_N\lambda\left(v_u S_{j2} + v_d S_{j1}\right) + \sqrt{2}\left(2\lambda_N\kappa v_s - 4\lambda_N^2 v_s + \lambda_N A_N\right) S_{j3}, \tag{9}$$

$$V_{h_ih_jRR} = -\lambda_N\left[2\kappa S_{j3}S_{i3} - \lambda(S_{j1}S_{i2} + S_{i1}S_{j2})\right] - 4\lambda_N^2 S_{j3}S_{i3}, \tag{10}$$

$$V_{h_ih_jMM} = \lambda_N\left[2\kappa S_{j3}S_{i3} - \lambda(S_{j1}S_{i2} + S_{i1}S_{j2})\right] - 4\lambda_N^2 S_{j3}S_{i3}, \tag{11}$$

$$V_{a_iRM} = -2\lambda_N(-\lambda v\cos 2\beta P_{i1}/\sqrt{2} + \sqrt{2}\kappa v_s P_{i1}) + \sqrt{2}\lambda_N A_N P_{i2}, \tag{12}$$

$$V_{a_ia_jRR} = 2\lambda_N(\lambda\sin\beta\cos\beta P_{i1}P_{j1} + \kappa P_{i2}P_{j2}) - 4\lambda_N^2 P_{i2}P_{j2}, \tag{13}$$

$$V_{a_ia_jMM} = -2\lambda_N(\lambda\sin\beta\cos\beta P_{i1}P_{j1} + \kappa P_{i2}P_{j2}) - 4\lambda_N^2 P_{i2}P_{j2}, \tag{14}$$

$$V_{h_iNN} = -\sqrt{2}\lambda_N S_{i3} \qquad V_{a_iNN} = \sqrt{2}i\lambda_N P_{i2}\gamma^5, \tag{15}$$

$$V_{\chi_iRN} = -\lambda_N\frac{N_{i5}}{2\sqrt{2}} \qquad V_{\chi_iMN} = \lambda_N\frac{iN_{i5}\gamma^5}{2\sqrt{2}}. \tag{16}$$

III. RENORMALIZATION SCHEME

To calculate the neutrino/sneutrino contribution to the Higgs mass, we must calculate the one-loop Higgs propagator and choose a renormalization scheme. Here we follow [10] and choose the mixed renormalization scheme (other schemes give similar results). We choose the following parameter set

$$M_Z,\ M_W,\ M_{H^\pm},\ e,\ \underbrace{t_{H_u},\ t_{H_d},\ t_{H_s},}_{\text{on-shell scheme}}\ \underbrace{\tan\beta,\ \lambda,\ v_s,\ \kappa,\ A_\kappa}_{\overline{\text{DR}}\text{ scheme}}\ , \tag{17}$$

where $t_{H_u}, t_{H_d}, t_{H_s}$ are the tadpoles of the CP-even Higgs fields. Since we concentrate on the right-handed nuetrino/sneutrino contributions, the input parameters from the gauge interaction part need not be renormalized. For the parameters which need renormalization, we replace them by the renormalized ones plus the corresponding counterterms:

$$\begin{aligned}
&t_{H_u} \to t_{H_u} + \delta t_{H_u}, && \tan\beta \to \tan\beta + \delta\tan\beta \\
&t_{H_d} \to t_{H_d} + \delta t_{H_d}, && \lambda \to \lambda + \delta\lambda \\
&t_{H_s} \to t_{H_s} + \delta t_{H_s}, && \kappa \to \kappa + \delta\kappa \\
&v_s \to v_s + \delta v_s, && A_\kappa \to A_\kappa + \delta A_\kappa\ .
\end{aligned} \tag{18}$$

In the following we will show how to determine the counter terms in the mixed renormalization scheme.

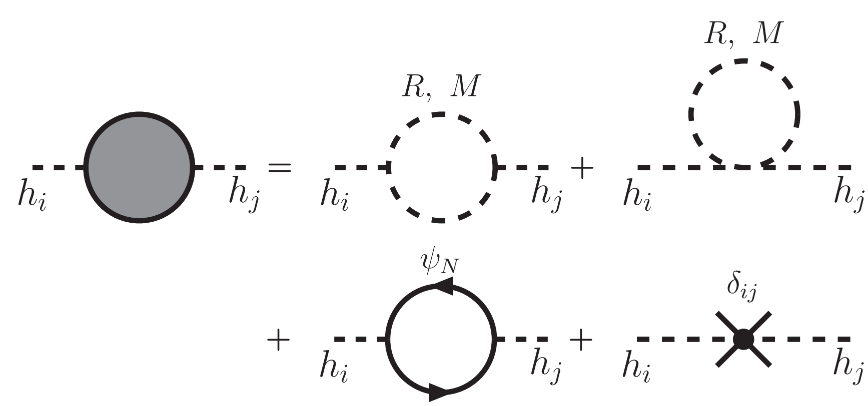

FIG. 1: Feynman diagrams for the two-point renormalized Higgs functions.

First, the Higgs doublet and singlet fields are replaced by the renormalized ones:

$$\begin{aligned} H_u \to \sqrt{Z_{H_u}}\, H_u &= \left(1+\frac{1}{2}\delta Z_{H_u}\right) H_u \\ H_d \to \sqrt{Z_{H_d}}\, H_d &= \left(1+\frac{1}{2}\delta Z_{H_d}\right) H_d \\ S \to \sqrt{Z_S}\, S \quad &= \left(1+\frac{1}{2}\delta Z_S\right) S\,. \end{aligned} \tag{19}$$

Then the renormalized two-point functions can be obtained from the Feynman diagrams shown in Fig. 1

$$\hat{\Sigma}_{H_iH_j}(k^2) \;=\; S_{ik}\; S_{jl}\; \hat{\Sigma}^S_{kl}(k^2) \qquad (i,j,k,l=1,2,3), \tag{20}$$

$$\hat{\Sigma}_{A_iA_j}(k^2) \;=\; P_{ik}\; P_{jl}\; \hat{\Sigma}^P_{kl}(k^2) \qquad (i,j,k,l=1,2), \tag{21}$$

where S_{ij} and P_{ij} are the matrix elements defined in Eqs.(5) and (6). The renormalization condition can be set as

$$\delta Z_{H_iH_i} = -\left.\frac{\partial \Sigma_{H_iH_i}(k^2)}{\partial k^2}\right|^{\rm div}_{k^2=(M^{(0)}_{H_i})^2} \qquad (i=1,2,3)\,, \tag{22}$$

where $M^{(0)}_{H_i}$ denotes the corresponding tree-level Higgs mass, and 'div' shows that we chose the $\overline{\rm DR}$ renormalization scheme which means that in the field renormalization only the divergent part $\Delta = 2/(4-D) - \gamma_E + \ln(4\pi)$ (γ_E is the Euler constant) is kept. The field renormalization constants $\delta Z_{H_d}, \delta Z_{H_d}, \delta Z_S$ are obtained by solving the equations

$$\delta Z_{H_iH_i} = |S_{i1}|^2 \delta Z_{H_d} + |S_{i2}|^2 \delta Z_{H_u} + |S_{i3}|^2 \delta Z_S \qquad (i=1,2,3)\,. \tag{23}$$

We use the field renormalization constants to determine the conterterms listed in Eq. (18). The detailed calculations are lengthy. In the following we only present the final results and give some necessary comments.

1. Tadpole parameters:

   The tadpole parameters are determined by the condition that they vanish after the renormalization. The Feynman diagrams are shown in Fig. 2 and the counter terms are determined by

$$\delta t_{H_i} = S_{ji}\, t^{(1)}_{h_j} \quad (i=u,d,s, \quad j=1,2,3)\,. \tag{24}$$

   where $t^{(1)}_{h_j}$ denote the one-loop Higgs tadpoles.

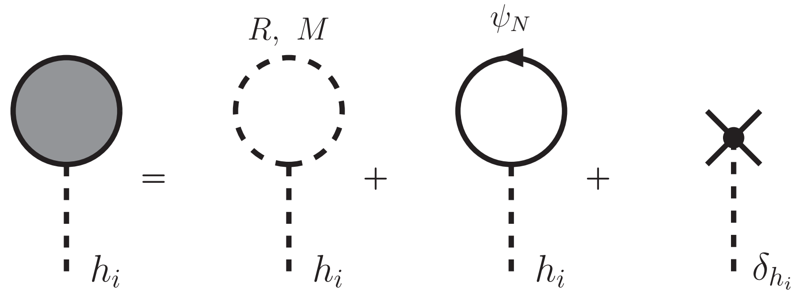

FIG. 2: Feynman diagram for the Higgs tadpoles.

2. The parameter $\tan\beta$:

$$\delta \tan\beta = \left[\frac{\tan\beta}{2}(\delta Z_{H_u} - \delta Z_{H_d})\right]_{\mathrm{div}} \quad . \tag{25}$$

3. The coupling λ:

$$\delta\lambda = \frac{e^2}{4\lambda M_W^2 s_W^2}\left[\Sigma_{P,11}(M_{P,11}^2)\right]_{\mathrm{div}} \quad .$$

   The self-energy $\Sigma_{P,11}$ is obtained from the self-energies in the mass eigenstate basis $\Sigma_{A_iA_j}$ $(i,j = 1,2,3)$ through

$$\Sigma_{P,11} = P_{i1}\,\Sigma_{A_iA_j}\,P_{j1} \quad . \tag{26}$$

4. The singlet Higgs vev v_s:

$$\delta v_s = -v_s \frac{\delta\lambda}{\lambda}\bigg|_{\mathrm{div}} \, , \tag{27}$$

5. The coupling κ:

   κ is renormalized through the neutralino renormalization whose diagrams are shown in Fig. 3. Note that we have different conventions of vev and thus the formula is a little different from Ref. [10].

$$\delta\kappa = \frac{1}{2v_s}\delta(\mathcal{M}_N)_{55} - \kappa\frac{\delta v_s}{v_s} \, . \tag{28}$$

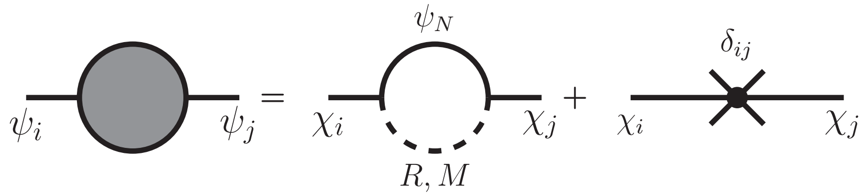

FIG. 3: Feynman diagrams for the renormalized two-point neutralino functions.

6. Tri-linear coupling A_κ:

   A_κ is renormalized by the CP-odd Higgs element $M^2_{P,22}$ and is given by

$$\delta A_\kappa = \Big[-\frac{1}{3\kappa v_s}\big[\Sigma_{P,22}\Big(M^2_{P,22}\Big) - \delta f\big] - A_\kappa\big[\frac{\delta\kappa}{\kappa} + \frac{\delta v_s}{v_s}\big]\Big]_{\rm div}\ , \tag{29}$$

   where the fuction f can be found in Ref. [10].

After the determination of the counterterms, we put these terms into the Higgs mass matrix which is shown in the Appendix. Also, by adding the loop contribution to the Higgs mass matrix, we can get the mass correction for the Higgs boson.

IV. NUMERICAL RESULTS

A. The right-handed neutrino/sneutrino correction to the Higgs boson mass

In our numerical calculation we concentrate on the SM-like Higgs boson which is the lightest CP-even Higgs boson dominated by the Higgs doublets. From the superpotential in Eq. (1) we can see that the right-handed neutrino/sneutrino interacts with the doublet only through the F-term of the singlet Higgs S, and thus the parameter λ will play an important role in the correction to the Higgs boson mass. To show this, we scan the parameter space in $0 < \lambda,\ \kappa,\ \lambda_N < 1$, $2 < \tan\beta < 50$, while other mass parameters vary in the range at TeV scale. The correction to the Higgs boson mass is shown in Fig. 4. From the figure we can see that when λ approaches to zero, the correction will approach zero; when λ is at order 1, the right-handed neutrino/sneutrino will alter the mass significantly. Thus, if λ is not small, then the right-handed neutrino/sneutrino contribution to the Higgs boson mass must be taken into account.

Now we check the SUSY limit in the right-handed neutrino/sneutrino sector. From Eq. (7) we can see that with $M_{\tilde N}$ and A_N approaching 0, the right-handed neutrino/sneutrino sector has a SUSY limit for $\kappa v_s^2 = \lambda v_u v_d$. In our second scan, we assume the relation

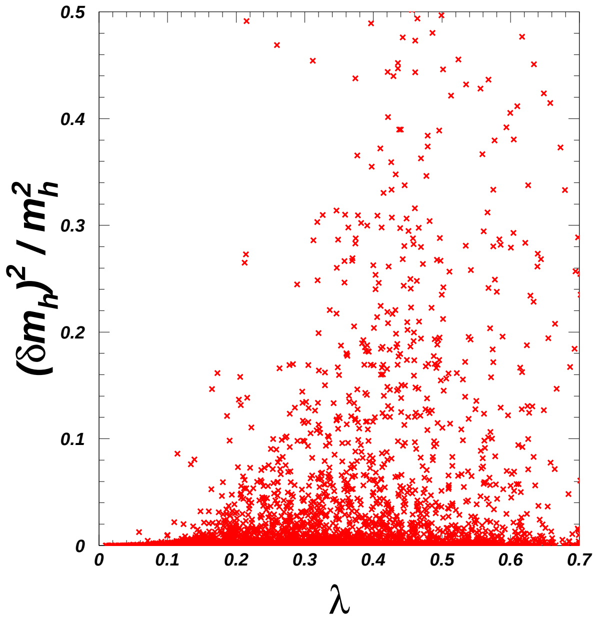

FIG. 4: The right-handed neutrino/sneutrino contribution to the SM-like Higgs boson mass versus the coupling λ.

$\kappa v_s^2 = \lambda v_u v_d$ and let the NMSSM parameter λ, κ, $\tan\beta$, A_λ, A_κ vary randomly. We fix $\lambda_N = 0.9$ and let $M_{\tilde{N}}$ and A_N vary randomly. The results are shown in Fig. 5. The results show that with $\sqrt{M_{\tilde{N}} A_N}$ approaching zero, the Higgs mass correction approaches zero, which confirms the SUSY limit.

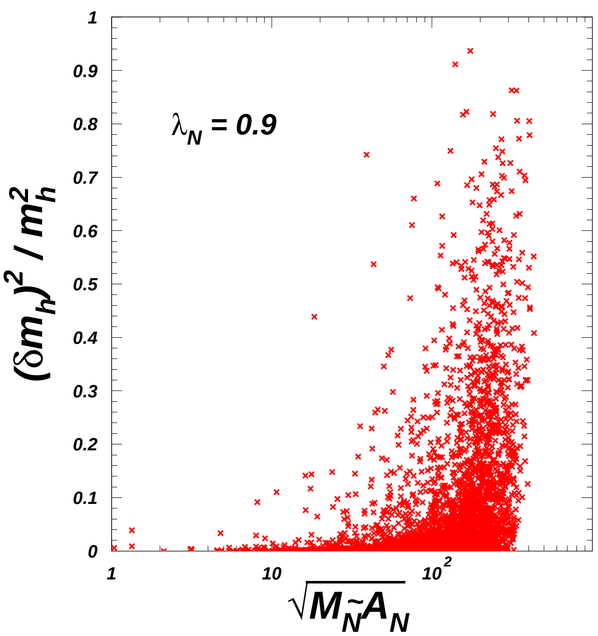

FIG. 5: The right-handed neutrino/sneutrino contribution to the SM-like Higgs boson mass versus $\sqrt{M_{\tilde{N}} A_N}$.

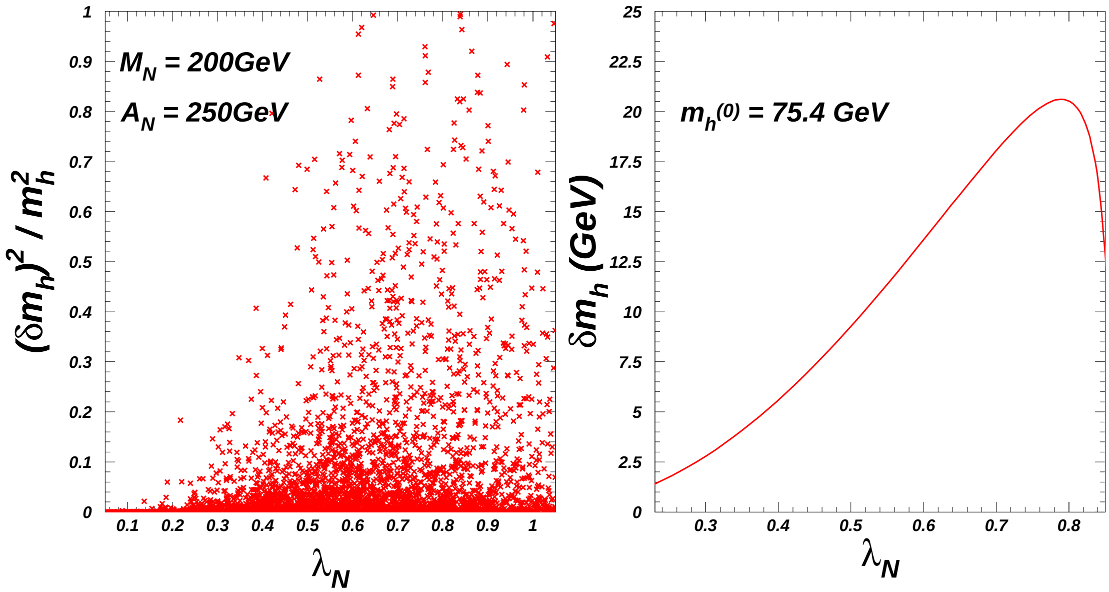

FIG. 6: The right-handed neutrino/sneutrino contribution to the SM-like Higgs boson mass versus λ_N

From the superpotential in Eq. (1) we can also see that the right-handed neutrino/sneutrino couples to the Higgs sector through the parameter λ_N. So, as λ_N approaching zero, the right-handed neutrino/sneutrino should decouple form the NMSSM sector. To check this numerically, we vary the NMSSM parameters and λ_N randomly while fixing $M_{\tilde{N}} = 200$GeV and $A_N = 250$GeV. The results are shown in the left panel of Fig. 6, which shows that the correction to the Higgs mass will approach zero as λ_N approach zero. To see this more clearly, we choose one benchmark point of the parameter set, for which the tree-level Higgs mass is 75.4 GeV, and vary λ_N from 0.2 to 0.85. The results are shown in the right panel of Fig. 6. We can see that δm_h increases as λ_N increases.

It is well known that the Higgs mass can be enhanced by the hierarchy between the SM particles and their SUSY partners. In the right-handed neutrino/sneutrino sector, the mass hierarchy between sneutrino and neutrino is controlled by the soft parameters $M_{\tilde{N}}$ and A_N. In order to show the dependence on the mass splitting, we chose a benchmark point of NMSSM, keeping $\lambda_N = 0.3$. Then we scan the parameters in the range of 0GeV $< M_{\tilde{N}} <$ 1000GeV ,-1000GeV $< A_N <$ 1000GeV randomly. The results are shown in Fig. 7, in which the left panel shows δm_h versus $M_{\tilde{N}}$ and the right panel shows δm_h versus m_R^2/m_N^2. From this figure we can see that as $M_{\tilde{N}}$ increases (the mass slitting between sneutrino and neutrino also increases as shown in Eq. (7)), the mass correction increases.

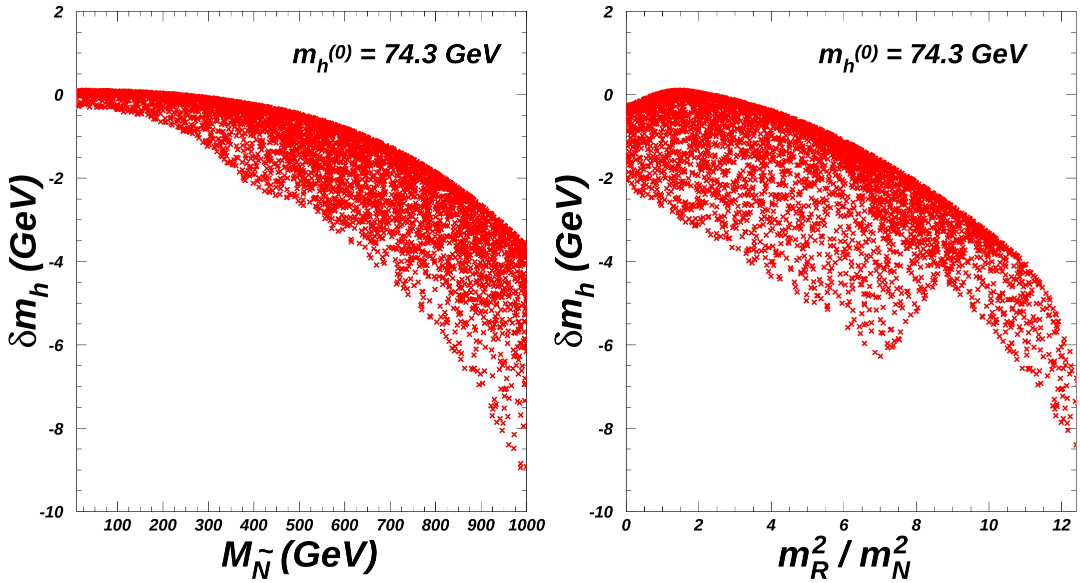

FIG. 7: The right-handed neutrino/sneutrino contribution to the SM-like Higgs boson mass versus the sneutrino soft mass $M_{\tilde{N}}$ and the ratio m_R^2/m_N^2 (for m_R and m_N, see Eq. (7)).

B. Higgs mass with all loop corrections under current experimental constraints

In the preceding section we only considered the loop corrections from the right-handed neutrino/sneutrino. Of course, the loop corrections from other particles (especially the top and stop) should also be taken into account. In our following numerical study, we include all available loop corrections by using the package NMSSMTools [11]. Since the right-handed neutrino/sneutrino is a gauge singlet, it will not change the Higgs decay or the annihilation of the dark matter. So, we just add the right-handed neutrino/sneutrino correction to the Higgs boson mass in the NMSSMTools. Then we scan the NMSSM parameter space in the range:

$$\begin{aligned} &0 < \lambda,\ k < 1, \quad 2 < \tan\beta < 50, \\ &0 < (\mu, M_1 = M_2/2 = M_3/6,\ m_{\tilde{Q}},\ m_{\tilde{t}} = m_{\tilde{b}} = m_{\tilde{\tau}} = m_{\tilde{\mu}}) < 1 \text{ TeV}, \\ &-1 \text{ TeV} < (A_\lambda,\ A_\kappa,\ A_t = A_b = A_\tau = A_\mu) < 1 \text{ TeV}. \end{aligned} \tag{30}$$

For the neutrino/sneutrino sector, we set $\lambda_N = 0.5$ and scan $M_{\tilde{N}},\ A_N$ in the range

$$0 < M_{\tilde{N}} < 1 \text{ TeV}, \quad -1 \text{ TeV} < A_N < 1 \text{ TeV}. \tag{31}$$

In our scan we consider the following experimental constraints [12]: (1) We require the lightest neutralino $\tilde{\chi}_1^0$ to account for the dark matter relic density $0.105 < \Omega h^2 < 0.119$;

(2) We require the SUSY contribution to explain the deviation of the muon a_μ, i.e., $a_\mu^{\rm exp} - a_\mu^{\rm SM} = (25.5 \pm 8.0) \times 10^{-10}$ at 2σ level; (3) The LEP-I bound on the invisible Z-decay, $\Gamma(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 1.76$ MeV, and the LEP-II upper bound on $\sigma(e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_i^0)$, which is 5×10^{-2} pb for $i > 1$, as well as the lower mass bounds on the sparticles from the direct searches at LEP and the Tevatron; (4) The constraints from the direct search for the Higgs bosons at LEP-II, including the decay modes $h \to h_1 h_1, a_1 a_1 \to 4f$, which limit all possible channels for the production of the Higgs bosons; (5) The constraints from B-physics observables like $B \to X_s \gamma$, $B_s \to \mu^+\mu^-$, $B^+ \to \tau^+ \nu$, $\Upsilon \to \gamma a_1$, the a_1–η_b mixing and the mass difference ΔM_d and ΔM_s; (6) The newest results for Higgs, top and stop results of the LHC. These constraints have been encoded in the package NMSSMTools [11]. In addition to the above experimental limits, we also consider the constraint from the stability of the Higgs potential, which requires that the physical vacuum of the Higgs potential with non-vanishing vevs of Higgs scalars should be lower than any local minima.

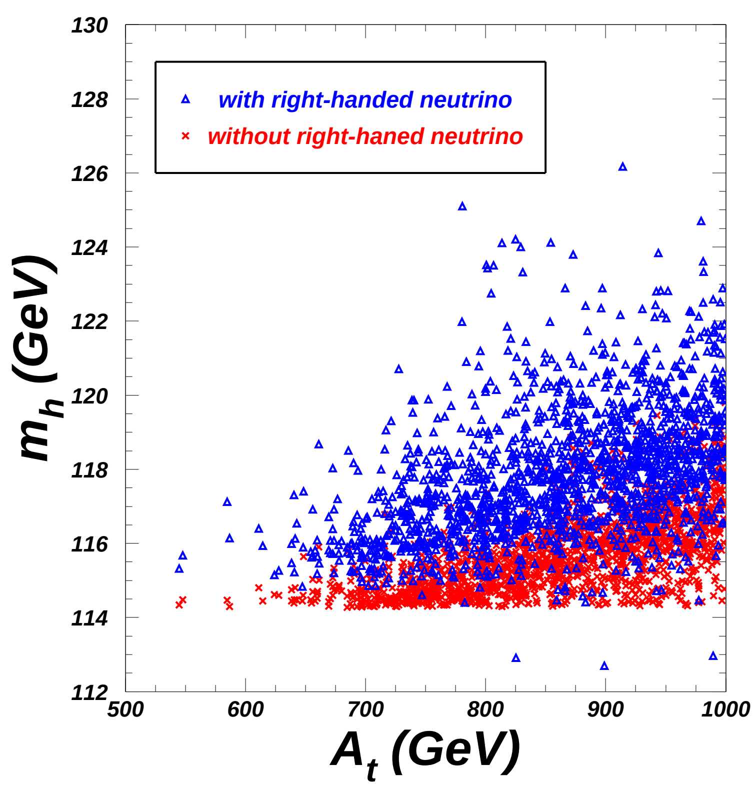

FIG. 8: The loop-corrected mass of the SM-like Higgs with or without the right-handed neutrino/sneutrino contribution.

The numerical results of our scan are shown in Fig. 8 in which we show the SM-like Higgs mass versus the tri-linear parameter A_t. Again we see that the contribution of the

right-handed neutrino/sneutrino is sizable, which helps to push up the SM-like Higgs boson mass and thus makes the NMSSM more natural.

V. SUMMARY

In order to have massive neutrinos, the right-handed neutrino/sneutrino superfield must introduced in SUSY. In the framework of NMSSM such an extention will dynamically lead to a TeV-scale Majorana mass for the right-handed neutrino. Further, through the couplings SNN and SH_uH_d, the SM-like Higgs boson can naturally couple with such TeV-scale right-handed neutrino/sneutrino. As a result, the right-handed neutrino/sneutrino may significantly contribute to the Higgs boson mass. In this work we performed an explicit calculation and found that the Higgs boson mass can indeed be sizably altered by the right-handed neutrino/sneutrino. Such new contribution can help to push up the SM-like Higgs boson mass and thus make the NMSSM more natural.

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Appendix

Here we list the analytical renormalized formula for the elements of the Higgs mass matrix. Although they can be found in Ref. [10], we checked them and corrected some typos. Note that β_B denotes the tree-level β and the $c_X,\ s_X,\ t_X$ denote respectively $\cos X$, $\sin X$ and $\tan X$.

The scalar 3×3 mass matrix M_S^2 in the basis $h^S = (H_u, H_d, S)^T$ is given by the entries $M^2_{S_{ij}} = M^2_{S_{ji}}$ $(i,j=1,2,3)$ with

$$\begin{aligned} M^2_{S_{11}} = {} & \frac{e c_\beta c_{\beta_B}}{2M_W s_W c^2_{\Delta\beta}}[-t_{H_d} s_{\beta_B} t_{\beta_B} + t_{H_u} s_{\beta_B}(t_\beta t_{\beta_B} + 2)] \\ & + \frac{c^2_\beta}{c^2_{\Delta\beta}}[M^2_{H^\pm} + (M_Z^2 t_\beta^2 - M_W^2) c^2_{\Delta\beta}] + \frac{2\lambda^2 M_W^2 s_W^2 c_\beta^2}{e^2}, \end{aligned} \tag{32}$$

$$M^2_{S_{12}} = \frac{ec_\beta c^2_{\beta_B}}{2M_W s_W c^2_{\Delta\beta}}[t_{H_d} t_\beta t^2_{\beta_B} + t_{H_u}] - \frac{s_\beta c_\beta}{c^2_{\Delta\beta}}[M^2_{H^\pm} + (M^2_Z - M^2_W)c^2_{\Delta\beta}] + \frac{\lambda^2 M^2_W s^2_W s_{2\beta}}{e^2}, \quad (33)$$

$$M^2_{S_{13}} = \frac{c^2_\beta c^2_{\beta_B}}{v_s c^2_{\Delta\beta}}[t_{H_d} t_\beta t^2_{\beta_B} + t_{H_u}] + \frac{2M_W s_W s_\beta c^2_\beta}{ev_s c^2_{\Delta\beta}}[M^2_W c^2_{\Delta\beta} - M^2_{H^\pm}]$$

$$+ \frac{\lambda M_W s_W c_\beta v_s}{e}[2\lambda t_\beta - \kappa] + \frac{-4\lambda^2 M^3_W s^3_W s_\beta c^2_\beta}{e^3 v_s}, \quad (34)$$

$$M^2_{S_{22}} = \frac{ec_\beta c^2_{\beta_B}}{2M_W s_W c^2_{\Delta\beta}}[t_{H_d}(2t_\beta t_{\beta_B} + 1) - t_{H_u} t_\beta] \quad (35)$$

$$+ \frac{s^2_\beta}{c^2_{\Delta\beta}}[M^2_{H^\pm} + (M^2_Z t^{-2}_\beta - M^2_W)c^2_{\Delta\beta}] + \frac{2\lambda^2 M^2_W s^2_W s^2_\beta}{e^2}, \quad (36)$$

$$M^2_{S_{23}} = \frac{s_\beta c_\beta c^2_{\beta_B}}{v_s c^2_{\Delta\beta}}[t_{H_d} t_\beta t^2_{\beta_B} + t_{H_u}] + \frac{2M_W s_W s^2_\beta c_\beta}{ev_s c^2_{\Delta\beta}}[M^2_W c^2_{\Delta\beta} - M^2_{H^\pm}] \quad (37)$$

$$+ \frac{\lambda M_W s_W c_\beta v_s}{e}[2\lambda - \kappa t_\beta] + \frac{-4\lambda^2 M^3_W s^3_W s^2_\beta c_\beta}{e^3 v_s}, \quad (38)$$

$$M^2_{S_{33}} = \kappa A_\kappa \frac{v_s}{\sqrt{2}} + 2\kappa^2 v^2_s + \frac{t_{H_s}}{v_s} + \frac{2M_W s_W s_\beta c^2_\beta}{e^2 v^2_s c^2_{\Delta\beta}}[2M^2_{H^\pm} M_W s_W s_\beta - e(t_{H_d} t_\beta s^2_{\beta_B} + t_{H_u} c^2_{\beta_B})]$$

$$+ \frac{M^2_W s^2_W s_{2\beta}}{e^4 v^2_s}[2\lambda^2 M^2_W s^2_W s_{2\beta} - \kappa\lambda e^2 v^2_s - M^2_W e^2 s_{2\beta}] \quad . \quad (39)$$

The entries $M^2_{P_{ij}} = M^2_{P_{ji}}$ $(i,j = 1,2,3)$ of the pseudoscalar 3×3 mass matrix M^2_P in the basis $h^P = (a, a_s, G)^T$ read

$$M^2_{P_{11}} = \frac{2\lambda^2 M^2_W s^2_W c^2_{\Delta\beta}}{e^2} + M^2_{H^\pm} - M^2_W c^2_{\Delta\beta}, \quad (40)$$

$$M^2_{P_{12}} = \frac{M_W s_W s_{2\beta}}{ev_s c_{\Delta\beta}}[M^2_{H^\pm} - M^2_W c^2_{\Delta\beta}] - \frac{c_\beta c^2_{\beta_B}}{v_s c_{\Delta\beta}}[t_{H_u} + t_{H_d} t_\beta t^2_{\beta_B}]$$

$$+ \frac{\lambda M_W s_W c_{\Delta\beta}}{e^3 v_s}[2\lambda M^2_W s^2_W s_{2\beta} - 3\kappa e^2 v^2_s], \quad (41)$$

$$M^2_{P_{13}} = M^2_{H^\pm} t_{\Delta\beta} + \frac{M^2_W s_{2\Delta\beta}}{2e^2}[2\lambda^2 s^2_W - e^2] + \frac{ec_{\beta_B}}{2M_W s_W c_{\Delta\beta}}[t_{H_d} t_{\beta_B} - t_{H_u}], \quad (42)$$

$$M^2_{P_{22}} = -3A_\kappa \kappa \frac{v_s}{\sqrt{2}} + \frac{t_{H_s}}{v_s} - \frac{2M_W s_W s_\beta c^2_\beta c^2_{\beta_B}}{e^2 v^2_s c^2_{\Delta\beta}}[t_{H_u} + t_{H_d} t_\beta t^2_{\beta_B}]$$

$$+ \frac{M^2_W s^2_W s^2_{2\beta}}{ev^2_s c^2_{\Delta\beta}}[M^2_{H^\pm} - M^2_W c^2_{\Delta\beta}] + \frac{\lambda M^2_W s^2_W s_{2\beta}}{e^4 v^2_s}[2\lambda M^2_W s^2_W s_{2\beta} + 3\kappa e^2 v^2_s], \quad (43)$$

$$M^2_{P_{23}} = \frac{M_W s_W s_{2\beta}}{2ev_s c_{\Delta\beta}}[2M^2_{H^\pm} t_{\Delta\beta} - M^2_W s_{2\Delta\beta}] - \frac{c_\beta c^2_{\beta_B} t_{\Delta\beta}}{v_s c_{\Delta\beta}}[t_{H_u} + t_{H_d} t_\beta t^2_{\beta_B}]$$

$$+ \frac{\lambda M_W s_W s_{\Delta\beta}}{e^3 v_s}[2\lambda M^2_W s^2_W s_{2\beta} - 3\kappa e^2 v^2_s], \quad (44)$$

$$
M^2_{P_{33}} = M^2_{H^\pm}\tan^2\Delta\beta + \frac{M_W^2\sin^2\Delta\beta}{e^2}[2\lambda^2 s_W^2 - e^2] + \frac{e}{2M_W s_W c^2_{\Delta\beta}}[t_{H_d}c_{\beta-2\beta_B} - t_{H_u}s_{\beta-2\beta_B}] \quad . \tag{45}
$$

[1] J. Wess and B. Zumino, Nucl. Phys. **B70** (1974) 39; M.F. Sohnius, Phys. Rep. **128** (1985) 39;

[2] S. Dimopoulos and H. Georgi, Nucl. Phys. **B193** (1981) 150; N. Sakai, Z. Phys. **C11** (1981) 153.

[3] For a review, see, e.g., H. E. Haber and G. L. Kane, Phys. Rept. **117**, 75 (1985).

[4] J. E. Kim and H.P. Nilles, Phys. Lett. **B138** (1984) 150.

[5] See, e.g., J. R. Ellis, *et al.*, Phys. Rev. D**39**, 844 (1989); M. Drees, Int. J. Mod. Phys. A **4**, 3635 (1989); P. N. Pandita, Phys. Lett. B**318**, 338 (1993);Phys. Rev. D**50**, 571 (1994); S. F. King, P. L. White, Phys. Rev. D**52**, 4183 (1995); B. Ananthanarayan, P.N. Pandita, Phys. Lett. B**353**, 70 (1995); Phys. Lett. B**371**, 245 (1996); B. A. Dobrescu, K. T. Matchev, JHEP **0009**, 031 (2000); V. Barger, *et al.*, Phys. Rev. D**73**,(2006) 115010; R. Dermisek, J. F. Gunion, Phys. Rev. Lett. **95**, 041801 (2005); G. Hiller, Phys. Rev. D**70**, 034018 (2004); F. Domingo, U. Ellwanger, JHEP **0712**, 090 (2007); Z. Heng, *et al.*, Phys. Rev. D**77**, 095012 (2008); R. N. Hodgkinson, A. Pilaftsis, Phys. Rev. D**76**, 015007 (2007); Phys. Rev. D**78**, 075004 (2008); W. Wang, Z. Xiong, J. M. Yang, Phys. Lett. B**680**, 167 (2009); J. Cao, J. M. Yang, JHEP **0812**, 006 (2008); Phys. Rev. D**78**, 115001 (2008); U. Ellwanger, C. Hugonie and A. M. Teixeira, Phys. Rept. **496**, 1 (2010); J. Cao, Z. Heng and J. M. Yang, JHEP **1011**, 110 (2010); M. Maniatis, Int. J. Mod. Phys. **A25** (2010) 3505; U. Ellwanger, Eur. Phys. J. C **71**, 1782 (2011); J. Cao, *et al.*, JHEP **1206**, 145 (2012); JHEP **1203**, 086 (2012); JHEP **1210**, 079 (2012); Phys. Lett. B **703**, 462 (2011); arXiv:1303.2426 [hep-ph].

[6] D. G. Cerdeño, C. Muñoz and O. Seto, Phys. Rev. D **79**, 023510 (2009).

[7] R. Kitano and K. y. Oda, Phys. Rev. D **61** (2000) 113001.

[8] D. G. Cerdeno and O. Seto, JCAP **0908**, 032 (2009).

[9] J. Cao and J. M. Yang, Phys. Rev. D **71**, 111701 (2005) [hep-ph/0412315].

[10] K. Ender, T. Graf, M. Muhlleitner and H. Rzehak, Phys. Rev. D **85**, 075024 (2012).

[11] U. Ellwanger *et al.*, JHEP **0502**, 066 (2005).

[12] K. Nakamura *et al.* [Particle Data Group Collaboration], J. Phys. G **37**, 075021 (2010).